THE EFFECTS OF 'MACHINE' LAG ON A SERIAL CHOICE TASK WITH BALANCED AND BIASED INPUT FREQUENCIES

By J. Alfred Leonard

Medical Research Council, Applied Psychology Research Unit, Cambridge

An experiment is described which was designed to study the effects on rate or responding of (*a*) the frequencies of the various signals to which responses had to be made, and (*b*) the introduction of enforced delays between the appearance of a signal and the making of a response to it. Time taken to respond was found to be significantly lower when one of five alternative signals occurred much more frequently than others, than when the frequencies of all five signals were the same. Enforced delays in responding clearly shifted the modal response time when the input frequencies were biased.

The experiment has affinities to a number of practical tasks and was suggested by a problem arising in the sorting of letters by machine. Certain theoretical implications are also discussed regarding maximum possible rates of responding and the relation of response time to 'information'.

§ 1. Introduction

This study was prompted by a problem encountered by Conrad (1956) in relation to a Post Office automatic letter sorting machine. In this machine the operator is required to press keys according to a code in response to the addresses shown on envelopes which pass in front of him. The rate at which the envelopes appear is determined by the rate at which he makes his responses, each response bringing on the next envelope. The construction of the machine is such that there is a short period after each code is pressed before a second response can become effective and the question arises of whether this delay is likely significantly to slow down the operation of the machine.

In trying to answer this question one has recourse to two areas of research. The first is that which deals with fast serial responding in general, and with self-paced performance in particular. Here it was held for some time (see Hick and Bates 1950) that there was an upper limit of about two responses per second in situations which might be considered analogous in some respects to those encountered in the machine described above. From this point of view one had reason to assume that a delay imposed by the machine on the operator's ability to respond would not slow down performance appreciably, so long as it was substantially less than 0·5 sec. The second area of research concerns that in which information theory has been applied to a number of choice reaction and sorting tasks. These studies have revealed that the time taken per response is, on average, a linear function of the amount of 'information', in the information theory sense of the term, which is transferred from 'input' to 'output' (in the above case from address to keys) in making a response. Evidence and an admirable exposition of the theoretical case has been given by Crossman (1953). The time taken to make individual responses will vary. Some will be substantially slower than average, some appreciably faster. This is particularly the case where the frequencies of different signals are very different or, in the case of the letter-sorting machine, where some addresses are much commoner than others. Introducing differences in the frequencies reduces the information per stimulus as compared with cases in which frequencies are balanced, and the shortening of the *average* time per response resulting from this has been shown by Crossman (1953) and Hyman (1953) to be approximately proportional to the reduction of information. But in the first of these experiments the movement time itself was about 0·5 sec and in the other stimuli were given with relatively long intervals in between. Thus neither experiment showed whether, if the information per stimulus was reduced sufficiently by the unbalance in the frequencies of the different stimuli, the rate of two responses per second could be exceeded.

The present experiment was therefore undertaken with two questions in mind. Firstly, can responses be made at a rate appreciably above two per second, especially if the frequencies of different signals are very unequal ; and secondly does a minimum delay between responses slow down overall performance even though the delay is substantially shorter than 0·5 sec ?

§ 2. METHOD

Apparatus : The display consisted of a row of five small neon bulbs facing the subject with their long axes approximately at eye level about two feet from the subject's eyes. The spacing between centres of bulbs was 1·5 in. The control consisted of five conveniently spaced morse keys placed on a table in front of the subject. The control–display relationships were such that to achieve a correct response the subject had to press the key spatially corresponding to the bulb which was lit. Each pressing of a key, whether correct or wrong, brought on the next light in the series, so that the task was self-paced.

Stimulus sequences : Two series of stimuli were used, each series containing 50 stimuli. The *balanced* series was made up from a table of random numbers with the constraint that no runs of more than two were permitted, and with frequencies and digram structure balanced as closely as possible, i.e. ten stimuli for each of the five sources (2·3 bits per stimulus). The unbalanced or *biased* series was so constructed that one source occurred 34 times, and the other four sources four times each (1·5 bits per stimulus). The connections between the machine generating the series and the five signal lights could be permuted and different permutations were used for each trial.

Enforced delays in responding : The apparatus could be arranged either with or without a constraint upon the timing of responses. The constraint was obtained by disconnecting the response keys from the main part of the apparatus for about 0·35 sec after the beginning of each response. This meant that if the subject pressed a key within about 0·35 sec of a previous response, the display would not change. If the subject kept his finger on the key until the end of the ' dead time ' he could hear the apparatus click and the display would change. He would then have to release the key before being able to make the next response. Observation suggested that in fact waiting on the ' dead ' key did not happen very frequently.

Procedure : Two groups, each of six subjects, were used and they had somewhat different training procedures. In the first group, operating throughout without the enforced delay, three subjects were trained on balanced, and three on biased series, and during this time the balanced sequence did not have the same signal following itself without another in between. This training was followed by one session in which all subjects were given both types of series, half starting with balanced and half with biased. The next session, identical to that just described, was the test session. The second group operated with the enforced delay throughout, and was given both balanced and biased sequences throughout, three subjects starting with balanced, and three with biased on each session. The procedure on the test day was the same as for the first group. The pre-test experience of subjects in the first group was 1650 responses in five days, that for the second group was 1800 responses in three days. It is not thought that these differences in procedure are likely to have had any important effect on the results.

On the test day subjects were given two blocks of six trials each containing 50 stimuli : the first trial in each block was considered a warm-up trial and the results of the five remaining trials were used. Permutations of the biased sequence were chosen in such a way that each of the five signal lamps was lit with greater frequency than the others on one trial during the test. Subjects were told in advance of each trial which this lamp would be. They were instructed to operate as fast and as accurately as they could and were told their time and their error score after each trial.

Scoring : Total times per trial were obtained from a decatron timer to the nearest 0·1 sec. Errors were obtained from an electromagnetic counter. Distributions of individual response times were obtained from a distribution meter on loan from the G.P.O. who also made this piece of equipment. The distribution meter is designed to sort each interval between successive responses into one of eleven categories. The size of categories used was :

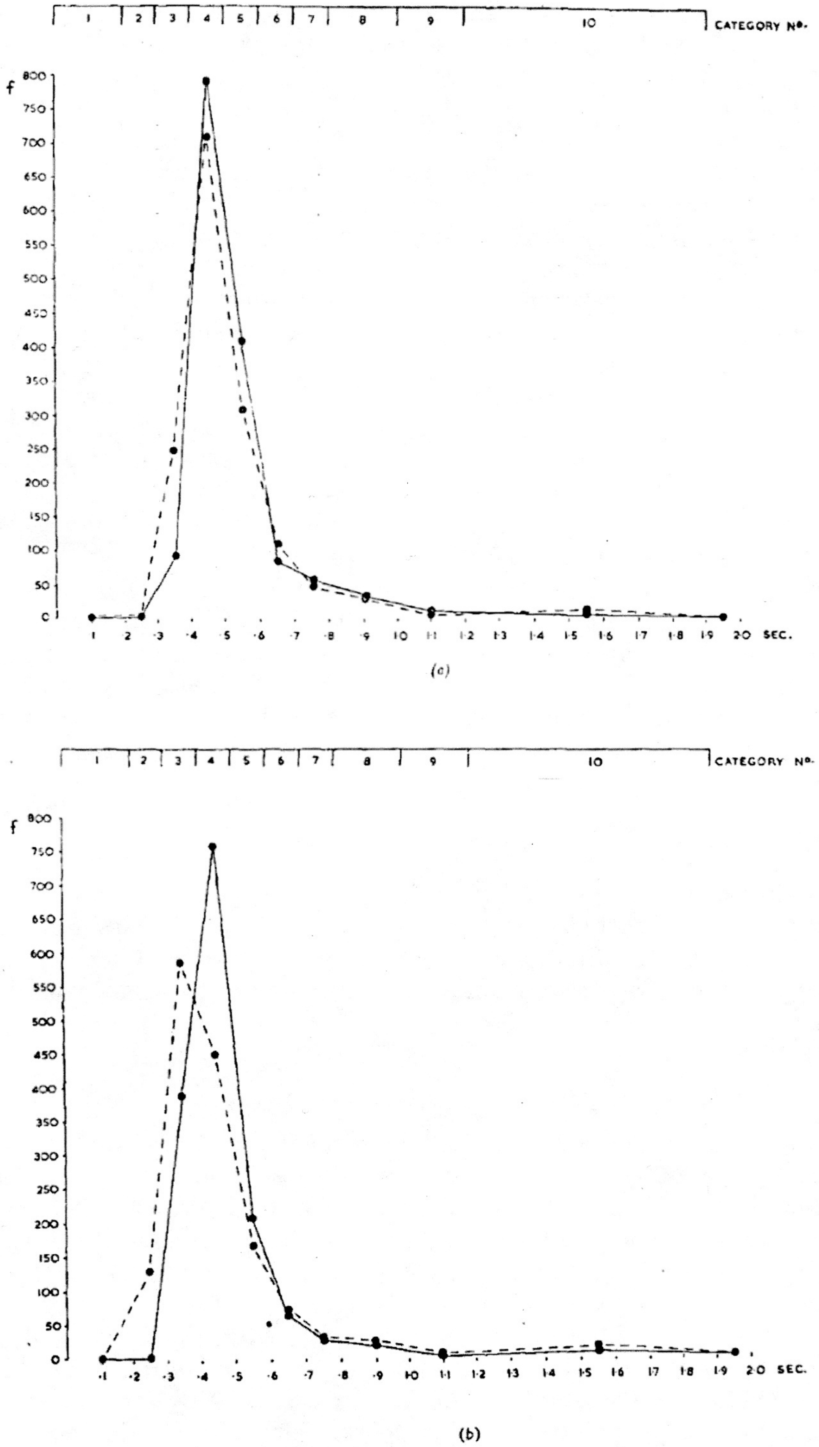
Category	1	2	3	4	5	6	7	8	9	10	11
Duration in sec:	<0·2	<0·3	<0·4	<0·5	<0·6	<0·7	<0·8	<1·0	<1·2	<1·9	1·9 and longer

For the purpose of presenting results the readings contained in the largest category were not included. In the great majority of cases this category contained only the reading obtained for the first response of each trial, which was large because circuits were not arranged to cancel the device when starting the series.

§ 3. RESULTS

Mean values of response times and error percentages are presented in Table 1. It can be seen that both groups took less time with biased than with balanced series. All members of the group working without enforced delays and four out of the six working with enforced delays showed this effect. The rates of responding rose appreciably above two per second, especially among the first group of subjects.

The distributions of response times are graphed in the figure and confirm the indications of Table 1 regarding the effects of enforced delays. For the balanced series the distributions with and without delay are closely similar, although the latter is shifted slightly to the left. For the biased series the distribution with delay is shifted very clearly to the left so that the mode falls in category 3 instead of category 4. The delay thus seems appreciably to have affected the speed of response with the biased series, but not with the balanced.



Frequencies of responses (*f*) in different time-categories.

(a) Balanced series. **(b)** Biased series. Dotted lines : without enforced delays in responding. Solid lines : with enforced delays. The frequencies for individual subjects are given in Appendix, Table 3.

Table 1. Mean Times, Rates of Responding and Error Percentages

Series	Measure	Group working without enforced delay	Group working with enforced delay
Balanced	Secs per response	0·485	0·498
	Responses per sec	2·06	2·01
	Percent errors	4·1	3·5
Biases	Secs per response	0·419	0·453
	Responses per sec	2·39	2·21
	Percent errors	3·2	2·9

The mean times were calculated from the times per trial. It should be noted that these mean times per response include the duration of the enforced delay response. The rates of responding are the reciprocals of the mean times; the errors are expressed as percentages of the total number of responses in each condition, i.e. 1500. Data for individual subjects are given in the Appendix, Table 2.

An analysis of variance carried out on subjects' mean times per response showed a highly significant effect between balanced and biased series. The effects due to the use of the enforced delay, although appreciable, especially with the biased series were not significant, nor was the interaction between delay and type of series. The effect of order of presentation was not significant but the interaction between this effect and that due to the use of balanced or biased series was significant.

§ 4. Discussion

From a practical point of view the results obtained in the present experiment throw some light on the possibility of detrimental effects of machine lags in those cases in which the operator can see the next signal to be dealt with without being able to respond as soon as he is ready to do so. One can think of a number of situations in which this might apply, i.e. where there is a measure of independence between the rate at which signals arrive and the rate at which operators can follow, the limiting factor being lags in the control system such as times required for the system to be cleared. It is evident from the distributions of response times that since operators are in fact able to deal more rapidly with a biased input such delays may be more detrimental in such cases.

Having said this much it is necessary to make certain qualifications. The two most important are that in the present experiment only one duration of delay was used, as well as only one amount of bias. Concerning the latter point it may be doubted whether there are many instances in which the bias used here is exceeded in real life situations, except perhaps in some inspection tasks. On the other hand the duration of the delay was chosen somewhat arbitrarily to be below the mean response rates. While it seems reasonable to assume that duration of delay as a function of mean response rate will have effects of varying magnitude, inspection of the distributions makes it clear that it is not at present possible to predict the size of the effects. The use of the delay did not seem to produce a simple shift, but was apparently compensated for to some extent, so that in the case of the balanced input frequencies the difference of mean response times was relatively small. This leads to a further qualification. The subjects in the present experiment were operating at or near the limit of their performance over very short periods of time. The largest difference in mean response times found was 0·066 sec, and the effect due to the delay with the biased series was only 0·034 sec on the average. No evidence is available to help one to say what effects would be when performance had to be continued for longer periods, say 45 minutes or so at a time for several weeks on end.

The main point of interest from the theoretical point of view is concerned with the performance of subjects in the group working without enforced delays. When operating with the balanced input they were performing at an average rate of about two responses per second and were able to improve on that rate when operating with the biased input. In other words, they were able to take advantage of the reduced information content. Now, while on the one hand there is reason to believe that the 'limit' of two responses per second for manual responding (Hick and Bates 1950) can be exceeded under certain conditions, variation in information content achieved by varying the number of *equiprobable* alternatives does not appear to be one of these conditions (Alluisi, Muller and Fitts 1957). In the case of the experiment just presented reducing the information content by varying the *bias* did however have a significant effect on performance. Thus a simple experiment is suggested to test the hypothesis that one of the pre-conditions for obtaining a two-responses per second limit is equiprobability rather than information content of alternative stimuli : one would have to compare self-paced performance under at least three conditions, e.g. 5-choice equiprobable, 3-choice equiprobable, and 5-choice with 68 per cent bias (in the last two of these conditions the average information per stimulus is about the same). On the above argument one would expect there to be no difference in mean times to respond between the first two conditions, but a significant difference between these two and the third condition. It is hoped to carry out such an experiment in the future.

APPENDIX

Table 2 shows the mean times (total times per trial summed for five trials and divided by 250) for each of the twelve subjects, and their error percentages (errors summed for five trials and expressed as a percentage of 250).

Table 2. Individual Subjects' Mean Times per Response and Error-Percentages

	Balanced series		Biased series	
	Time per Response	Errors	Time per Response	Errors
Without enforced delay	Seconds	per cent	Seconds	per cent
A	0·496	3·2	0·420	3·2
B	0·447	2·8	0·397	2·4
C	0·512	5·6	0·428	2·4
D	0·437	4·0	0·396	2·4
E	0·574	4·0	0·461	4·0
F	0·444	4·8	0·410	4·8
With enforced delay				
G	0·459	5·2	0·437	3·2
H	0·466	5·2	0·488	1·2
I	0·561	2·8	0·426	3·6
J	0·510	3·2	0·508	4·4
K	0·509	2·8	0·439	2·4
L	0·484	2·0	0·417	2·8

Table 3. Individual Subjects' Response Distributions. x=balanced, y=biased. The letter indicating the series given first is in italics

Category		<0·2	<0·3	<0·4	<0·5	<0·6	<0·7	<0·8	<1·0	<1·2	<1·9	Sec
Subject												
Without enforced delay												
A	x	—	—	8	133	84	9	6	3	1	1	245
	y	—	19	102	79	23	9	5	7	1	—	245
B	x	—	1	51	144	29	13	4	1	—	1	244
	y	—	34	86	78	31	6	4	1	—	3	243
C	*x*	—	—	44	97	49	28	12	10	2	3	245
	y	—	12	102	79	24	11	8	4	2	3	245
D	x	—	1	60	137	44	3	1	—	—	—	246
	y	—	49	80	70	31	14	1	1	—	—	246
E	*x*	—	—	10	80	64	48	21	14	2	5	244
	y	—	9	88	70	37	20	6	10	1	4	245
F	*x*	—	—	72	118	36	7	5	3	—	3	244
	y	—	4	128	71	19	12	6	1	—	4	245
Total	x	0	2	245	709	306	108	49	31	5	13	1468
	y	0	127	586	447	165	72	30	24	4	14	1469
With enforced delay												
G	x	—	—	16	178	40	5	3	1	1	1	245
	y	—	—	73	129	30	8	3	2	—	2	247
H	x	—	—	39	137	44	13	8	2	—	2	245
	y	—	—	44	126	39	14	13	9	—	—	245
I	*x*	—	—	1	86	98	22	21	12	1	5	246
	y	—	—	66	150	17	9	—	2	—	—	244
J	x	—	—	—	110	117	11	3	2	2	1	246
	y	—	—	2	138	74	19	7	2	—	5	247
K	*x*	—	—	8	136	59	22	7	7	3	1	243
	y	—	—	72	132	25	8	3	4	—	1	245
L	*x*	—	—	26	142	51	10	12	2	2	—	245
	y	—	—	130	82	22	8	2	—	1	—	245
Total	x	0	0	90	789	409	83	54	26	9	10	1470
	y	0	0	387	757	207	66	28	19	1	8	1473

Table 3 shows the distributions of times for individual subjects. These distributions were obtained by summing for each subject the separate distributions for five trials. They do not include the readings in the category above 2 seconds, so that there should be 245 readings for each subject. In actual fact there was a range of 243–247 which is thought to be attributable to mechanical counter faults. It is worth noting that means calculated from these distributions were all slightly larger than those shown in Table 1, on the average about 0·02 sec. Since these means were calculated with certain assumptions about distributions within categories the reliability of the data is thought to be satisfactory. It will be noticed that for the balanced series all the modes of the group working without enforced delays were in the interval labelled 0·5 sec, and four of the six modes in the group working with delays were similarly placed, the other two subjects having incidences of responses in that category only very little smaller than that of their modes in the next category. With the biased series all six subjects in the former group have modes in the category labelled 0·4 sec, but only one of the six subjects in the latter group achieved a mode in that category, the other five have their modes in the next category, i.e. in the same place as for the majority with the balanced series.

Description d'une expérience destinée à faire connaître l'action sur la vitesse de travail et sur la réponse produite par (*a*) les fréquence des signaux divers auxquel on devait répondre et (*b*) des retards forcés qu'on introduirait entre le signal et la réponse qu'il devait susciter. Le temps qui s'écoulait entre le signal et la réponse se trouvait être plus bref d'une espace significative quand un des cinq signaux alternants se produisait beaucoup plus fréquemment que les autres, que quand tous les cinq avaient la meme fréquence. Des retards imposés à la réponse avaient sans aucun doute pour résultat de changer le temps modale de la réponse.

Cette expérience se rapporte a plusieurs tâches pratiques et fut suggérée par un probléme qu'on rencontra en classant des lettres par moyen d'une machine. Il est question aussi d'implications théorétiques relatives aux vitasses maximales de réponse et à la relation du temps de la réponse à 'l'information'.

Es wird ein Experiment beschrieben, mit dem ermittelt werden sollte, wie (*a*) die Geschwindigkeit der Beantwortung verschiedener Signale durch die Frequenz dieser Signale beeinflusst wird und wie sich (*b*) die Einführung zwangsläufiger Pausen zwischen der Beantwortung eines Signals und der Darbietung des nächsten Signals auswirken. Die Zeit für die Beantwortung eines Signals war signifikant kürzer, wenn eines von 5 verschiedenen Signalen viel häufiger erschien als die anderen, als wenn die Frequenzen aller 5 Signale gleich waren. Zwangsläufige Verzögerung der Darbietung der Signale ändert deutlich das zeitliche Verhalten der Beantwortung.

Das Experiment hat Bedeutung für eine Anzahl praktischer Aufgaben und wurde angeregt durch das Problem der Brief-Sortier-Maschine. Es wurde auch in Zusammenhang mit der Frage der maximal-möglichen Reaktionsgeschwindigkeit und der Beziehung zwischen Reaktionsgeschwindigkeit und 'Information' diskutiert.

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